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ELECTRO-OPTIC LIGHT MODULATORS

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ABSTRACT

This report discusses the performance of KD₂P, GaAs and HMTA light modulators. KD₂P crystals have given excellent results in modulating a laser beam. Alignment of the crystal with relation to the light beam is very critical. GaAs appears at this time to be the best electro-optic crystal material for a light modulator in the infrared region between 0.9 and 16 microns. Strain-free GaAs can be grown with resistivities exceeding 10⁶ ohm-cm. At this time, the use of HMTA as a light modulator material does not appear promising.

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INTRODUCTION

The production of coherent light by lasers has stimulated interest in light communications systems and, therefore, in optical modulation techniques. The most generally useful of these employs the linear electro-optic (Pockel's) effect in crystals.

In an anisotropic medium, such as a crystal, the dielectric constant is a tensor with six independent components. Consequently, for light propagating in any given direction in the medium, two different plane polarizations at right angles to each other (and to the direction of propagation, of course) are possible. Waves of the two polarizations travel with different velocity, v , or have different refractive indices, c/v .

If beams of the two polarizations, to be denoted by the subscripts α and β , start together through the crystal, the retardation, Γ , (in radians), of one relative to the other after they traversed a thickness ℓ of crystal is

$$\Gamma = \frac{2\pi}{T} \left(\frac{\ell}{c/n_\alpha} - \frac{\ell}{c/n_\beta} \right) = \frac{2\pi\ell}{\lambda} \Delta n ,$$

where T is the period of the vibration, Δn is the difference in the refractive indices, and λ , the free space wavelength.

The electro-optic coefficient is usually defined in terms of

$$\left(\frac{\Delta n}{n_0^3 E} \right) = r_{63} = r_{41} , \quad (\text{for cubic structure}) ,$$

$$\Gamma = \frac{2\pi\ell}{\lambda} r_{41} n_0^3 \frac{V}{t} , \quad \text{for } E \perp (1, 1, 0) \text{ plane} ,$$

where

ℓ = path length of light

n_0 = index of refraction

$r_{63} r_{41}$ = electro-optic coefficients

$E\left(=\frac{V}{t}\right)$ = applied transverse field

t = thickness in direction of applied field

λ = wavelength

$$\Gamma = \frac{\sqrt{3}\pi\ell}{\lambda} r_{41} n_0^3 \frac{V}{t} , \quad \text{for } E \perp (1, 1, 1) \text{ plane ,}$$

$$\Gamma = \frac{2\pi}{\lambda} r_{63} n_0^3 V , \quad \text{for tetragonal structure (optically uniaxial) or for } E \perp (0, 0, 1) \text{ plane ,}$$

where r_{63} describes the effect of a field parallel to the optic axis and r_{41} , the effect of a field perpendicular to this axis.

The Pockel effect consists of a linear variation in refractive index due to electric field that is described in terms of the coefficients in

$$\frac{1}{n_1^2} x^2 + \frac{1}{n_2^2} y^2 + \frac{1}{n_3^2} z^2 + \frac{2}{n_4^2} yz + \frac{2}{n_5^2} zx + \frac{2}{n_6^2} xy = 1$$

by

$$\frac{1}{n_i^2} = \left(\frac{1}{n_i^2} \right)_{E=0} + \sum_{j=1}^3 r_{ij} E_j .$$

The difference in refractive indices, Δn , and retardation, Γ , depend linearly on field strength. It is this dependence of the retardation on field which is useful for the modulation of light. In the absence of a field, modulation is greatly simplified when there is no retardation. This may be accomplished either by the use of a cubic crystal, which is optically isotropic, or in an anisotropic crystal, by a beam of parallel light which is also parallel to the optical axis of the crystal. Cubic crystals are much to be preferred since the parallelism requirements in the use of an anisotropic crystal are very stringent, if the efficiency of the modulation is not to be reduced by natural birefringence of the crystal.

The crystals most commonly used in electro-optic modulators are KH_2PO_4 (KDP) and its isomorphs which are of tetragonal structure and, therefore, optically uniaxial. Their use has been dictated by their high electro-optic sensitivity and their ready preparation as large single crystals. (Modulation of light at frequencies as high as 16.5 Gc demonstrated by R. A. Myers, Reference 1.)

However, these crystals have a fundamental limitation in that their point group symmetry ($\bar{4}2m$) requires that the modulating field be along the light path. This arrangement necessitates the use of large voltages to produce useful retardation values and also makes optical modulator design more difficult, particularly at the higher frequencies, than would be the case for transverse modulating fields.

The properties of the cubic crystal class $\bar{4}3m$ of particular importance are

1. They respond to fields transverse to the light path, simplifying problems of modulator design and permitting reduction in the voltage by the use of a light path large compared with the distance over which the field is impressed; and
2. They are cubic and hence possess no natural birefringence. The problems of alignment and beam parallelism are, therefore, minimized as compared with those found in the use of naturally birefringent crystals such as KDP.

Table 1 compares the properties of several materials which have been used as optical modulators because of their linear electro optic effect.

The values of ϵ and $\tan \delta$ are important considerations for the modulator power necessary for a given retardation, since

$$\Gamma = \frac{2\pi \ell n_0^3 r_{41}}{\lambda} \quad E = \frac{2\pi \ell n_0^3 r_{41}}{\lambda} \left(\frac{2P_{\text{mod}}}{\omega \epsilon \tan \delta} \right)^{1/2},$$

where

P_{mod} = modulator power per unit crystal volume

ℓ = path length of light

ω = angular modulation frequency

$\tan \delta$ = loss tangent

ϵ = dielectric constant of the crystal

E = electric field across sample.

Hence, for a given modulator power, greater modulation can be obtained with materials of lower dielectric constant and lower loss tangent.

The requirement of a low dielectric constant in the microwave region is also important in the construction of wideband, high-frequency, traveling-wave modulators. Such schemes require a matching of the microwave and optical wave velocities over a broad frequency response; hence, the square root of the dielectric constant should be approximately equal to the index of refraction over the frequency range of interest (Reference 2). The requirement $\sqrt{\epsilon} = n_0$ is quite closely fulfilled for HMTA and GaAs. Figures 1 and 2 represent the tetragonal structure (KDP, ADP, KD_2P) and the cubic structure (HMTA, GaAs, CuCl, ZnS).

Table 1

Comparison of Electro-Optic Materials.

Crystal Material	ADP*	KDP	KD ₂ P	CuCl	ZnS	HMTA	GaAs
Crystal Structure	Tetragonal	Tetragonal	Tetragonal	Cubic	Cubic	Cubic	Cubic
Index of Refraction	1.525	1.51	1.51	1.93	2.546 ($\lambda = 0.4\mu$) 2.348 ($\lambda = 0.75\mu$)	1.5911 ($\lambda = 0.589\mu$)	3.50 ($\lambda = 1\mu$) 3.30 ($\lambda = 4\mu - 16\mu$)
Dielectric Constant	15.4	22	45	8	8.3	3.2	11-12
Loss Tangent	0.04	0.02	0.1	0.0015	—	0.001	0.0005
Electro-Optic Coefficient at 5460-5890 Å (cm/v)	r_{63} 6.34×10^{-10}	10.7×10^{-10}	23.6×10^{-10}	6.14×10^{-10}	2.13×10^{-10}	4.18×10^{-10} (RCA) 7.3×10^{-10} (AAI)	1.0×10^{-10} (at $\lambda = 1\mu$)
Retardation Voltage $V_{\lambda/2}$ at 5460 Å (pv)	r_{41} 24.5×10^{-10}	8.77×10^{-10}	8.8×10^{-10}	—	—	$0.465 - 0.625 \times 10^{-10}$	—
Longitudinal	9.6	7.5	3.4	—	—	—	—
Transverse	—	—	—	$7.2 \frac{\text{width}}{\text{length}}$	$10 \frac{\text{width}}{\text{length}}$ (at 6328 Å)	$127 \frac{\text{width}}{\text{length}}$ (at 6328 Å)	$13.3 \frac{\text{width}}{\text{length}}$ (at 1μ)
Spectral Range of Transparency	0.4-1.7	0.4-1.7	0.4-1.7	$0.4-20.5\mu$	0.4-?	$0.35-2\mu$	$1-16\mu$
Angular Field of View (degrees)	2	2	2	18	18	18	18

*ADP NH₄H₂PO₄ Ammonium dihydrogen phosphate
 KDP KH₂PO₄ Potassium dihydrogen phosphate
 KD₂P(KD^{*}P) KD₂PO₄ Potassium dideuterium phosphate
 HMTA N₄(CH₂)₆ Hexamethylenetetramine
 KTN KTa(X)Nb(1-x)O₃ Potassium Tantalate Niobate
 CuCl Cuprous Chloride
 GaAs Gallium Arsenide
 ZnS Zincblende

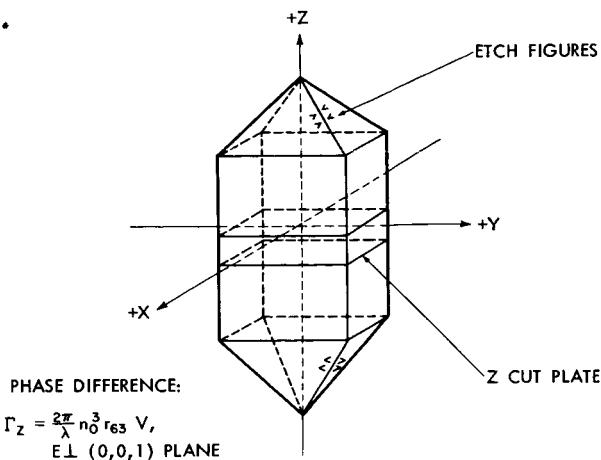


Figure 1—An ADP, KDP or KD_2P crystal with crystallographic axes labelled.

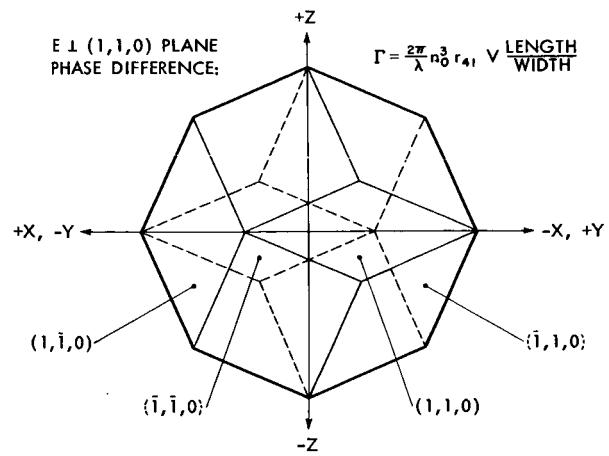


Figure 2—HMTA (Hexamethylenetetramine $N_4 (CH_2)_6$) crystal.

ISOMET ELECTRO-OPTIC LIGHT MODULATOR (MODEL 101B)

The active element in an isomet electro-optic light modulator (EOLM) 101B is a KD_2P (potassium dideuterium phosphate) crystal with faces polished normal to the crystallographic Z-axis. The crystal belongs to the class $\bar{4}2m$ and is normally uniaxial. It is placed between two transparent electrodes allowing light to pass in the same direction as the applied electric field. (Electrode transparency is 90 percent through the anti-reflecting coatings.) Figure 3 shows the arrangement of the EOLM 101B with detector and laser source.

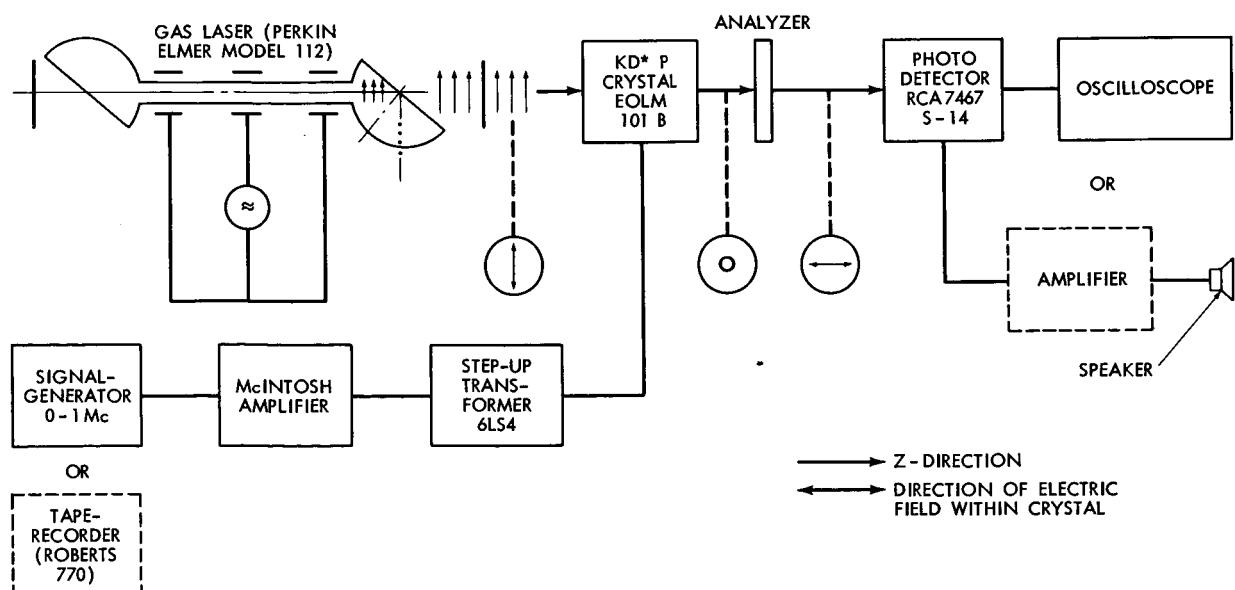


Figure 3—Arrangement for external modulation (EOLM 101B).

The collimated and polarized light beam of the He-Ne gaseous laser passes through the KD_2P crystal and the analyzer to the photo junction cell. With no field applied, the system is adjusted to pass a minimum of light (crossed polarizers). With a modulating voltage applied between crystal faces, elliptically polarized light in general emerges from the crystal because, as previously noted, the incident plane-polarized beam is split into two mutually perpendicular components which travel with different velocities within the crystal. Consequently, the analyzer passes a periodically varying amount of light, over a cycle, to the detector.

Figures 4a and 4b show the plots of relative light intensity transmitted by the analyzer versus voltage applied across the crystal (electric field in the Z-direction) for crossed polarizers and two conditions of bias. In order to achieve a reasonably linear transfer function, the electro-optic modulator must be biased either electrically or optically. The latter can be accomplished by producing an additional retardation by putting in series with the crystal a fixed retardation sheet, a quarter-wave-plate, properly oriented to obtain circularly polarized light.

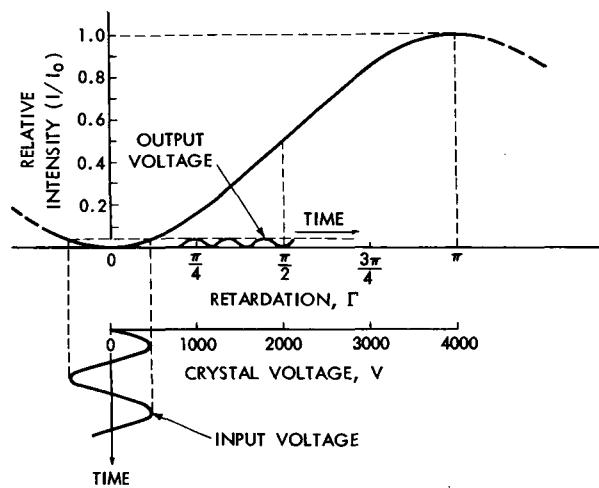


Figure 4a—Relative intensity vs. crystal voltage for zero bias.

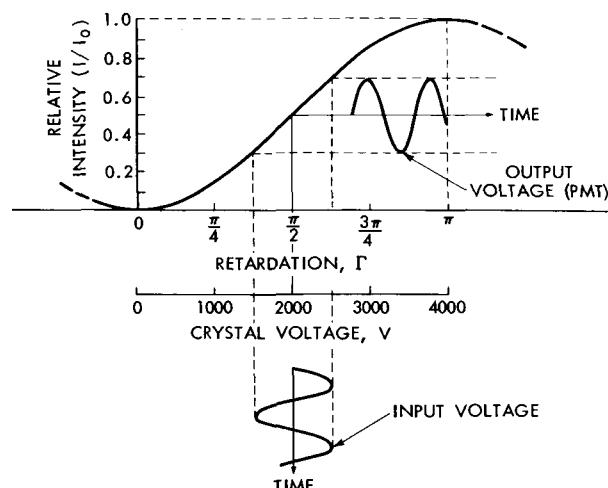


Figure 4b—Relative intensity vs. crystal voltage for quarter-wave bias.

It is observed from Figures 4a and 4b that for equivalent variations in Γ at the zero point and at the optically biased point, the latter gives a much larger variation in intensity; that is, at the biased point, modulation depth is greater. Finally, another advantage of the optical biasing is that 100 percent modulation can be obtained in the biased case with only half the peak-to-peak voltage that is required in the unbiased case. For a KD_2P crystal of the type discussed, we will get maximum transmission for a retardation of one-half wavelength which requires approximately 4000 volts at $\lambda = 6328 \text{ \AA}$.

One problem in connection with the desirable high fidelity of such a communication system is the question of the linearity of the crystal. Ideally, the change in intensity of the light which passes through the KD_2P crystal should follow exactly the change in voltage on the crystal. If the EOLM is biased with a quarter-wave plate, to normally transmit 50 percent, nearly linear response will

- be obtained, as seen in Figure 5. The EOLM 101B shows a frequency response (Figure 6) from dc current to 31 kc between ± 2 db, and a high percentage of distortion-free modulation. At operating point, $\lambda/4 = \pi/2$, with a maximum signal of 1/8 wave, the percentage modulation is 74 percent and the third harmonic is less than 3 percent of the fundamental, all other harmonics being negligible.

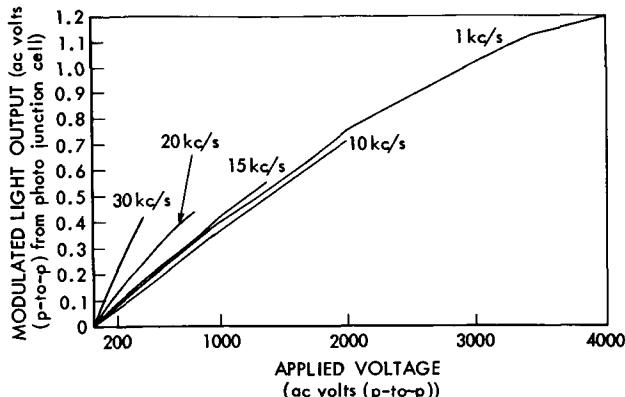


Figure 5-Linearity of modulator using KD_2P crystal.

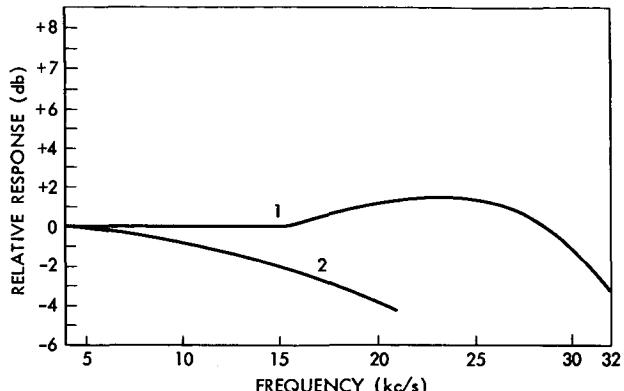


Figure 6-Frequency response of EOLM 101B.

301B MODULATOR

The EOLM 301B which has a higher frequency response differs from the EOLM 101B only in the electrode structure. In Model 301B, vacuum-deposited gold grids are applied directly to the face of the KD_2P crystal.

The vacuum-deposited gold grids provided on Model 301B extend the frequency response to 2 Mc. This grid network does not produce a completely uniform field; therefore, the retardation voltage $v_{\lambda/2}$ is approximately 5200 v at $\lambda = 6328 \text{ \AA}$. For the evaluation of Model 301B it was necessary to design and fabricate an electric drive circuit (modulator circuit).

Figure 7 shows the arrangement of the EOLM 301B with laser source, detector and additional components. An RCA photomultiplier tube (6199) with an S-11 spectral response was used as detector. Figure 8 shows the RF unit and Figure 9, the modulator. Subcarrier modulation, in effect, translates the spectrum of the audio frequencies to a higher frequency range where there are no piezo-electric resonances. Another benefit derived from subcarrier modulation is the elimination of "flicker" noise caused by low frequency fluctuation of the light source.

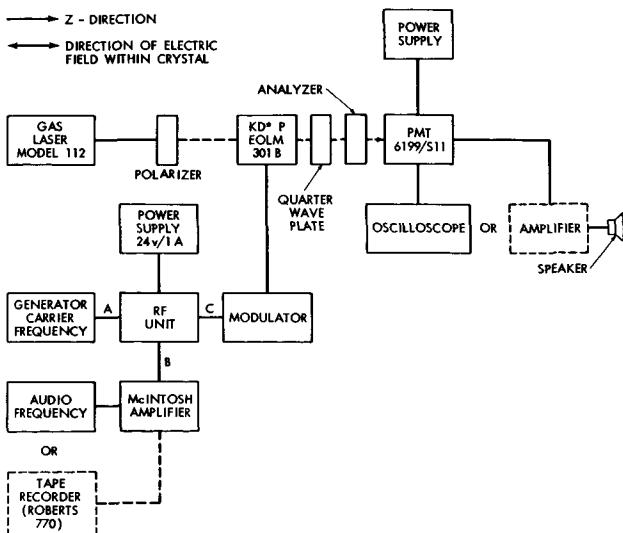


Figure 7—Arrangement for external modulation (EOLM 301B).

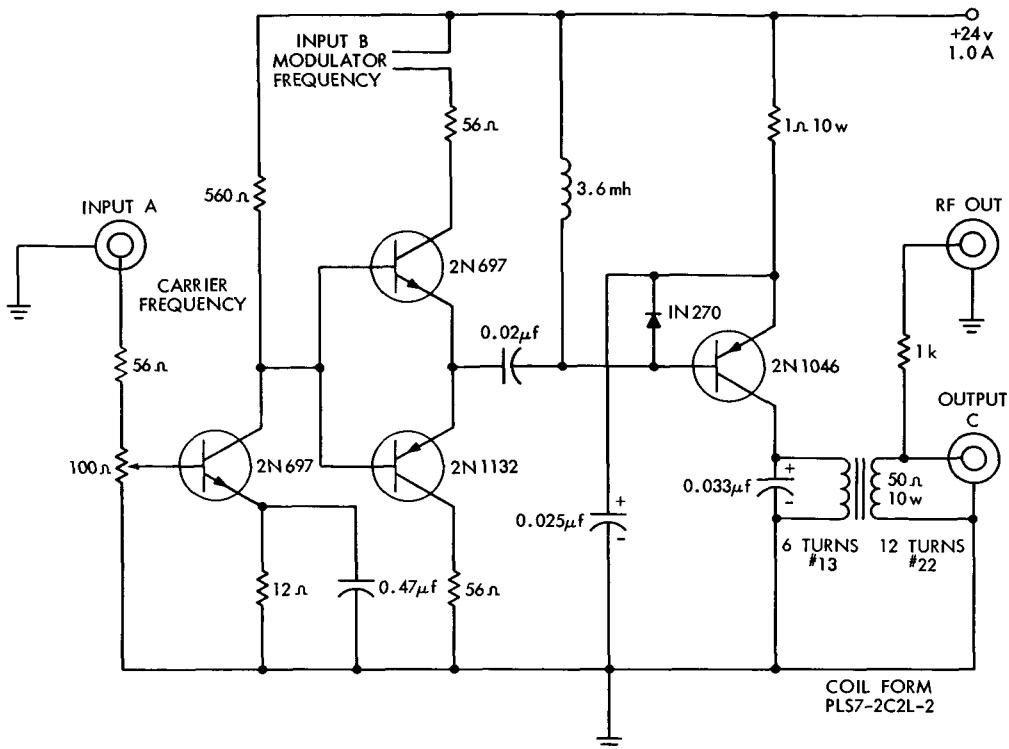


Figure 8—EOLM 301B RF unit.

The modulator circuit (RF unit and modulator) is completely transistorized. The RF unit has a common-emitter driver, a complementary-symmetry common-collector amplifier and a power stage. The output of the power stage is connected to the input of the modulator in which a resonance circuit with toroids core produces the necessary high modulation voltage.

The investigation of EOLM 301B with the transistorized modulator circuit shows that this arrangement is very useful for light modulation of any light source between 4,000 - 12,000 Å and modulation frequencies from dc current up to 2 Mc. (By modification of the RF circuits and using transistor with higher cutoff frequencies, EOLM 301B may be usable approximately up to 10 Mc/s.) The frequency response is also limited due to the resistance of the vacuum deposited gold grids.

Utilizing the modulator circuit shown in Figure 8, the crystal was modulated up to 3600 volts (p-to-p) at 1 Mc by using a dc power supply (22 v and 1.1a). The obtained bandwidth (3 db down from maximum) was ± 15 kc. The depth of modulation, $m = \sin \pi v_m / v_{\lambda/2}$, was 0.88 where v_m is the peak modulation voltage applied to the crystal and $v_{\lambda/2}$ is the retardation voltage, the voltage required for 100 percent modulation.

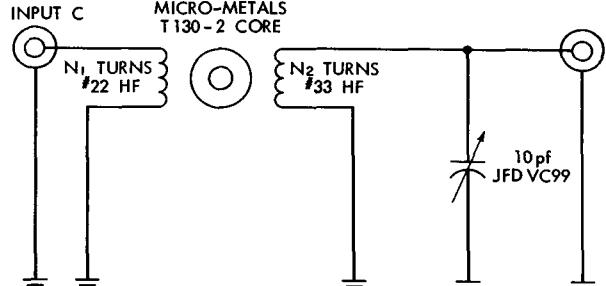


Figure 9—EOLM 301B modulator.

At the frequency of 2 Mc, the crystal was modulated up to 1100 volts (p-to-p) with the trimmer capacitance of 0.8pf. The obtained bandwidth was ± 50 kc and the depth of modulation was 0.33.

The modulator circuit, which contains a resonance circuit to produce the high voltage for the crystal, has a relatively small bandwidth. Figure 10 shows the KD₂P crystal EOLM 301B and Figure 11 shows the complete set up for the experiments. The performance of the subcarrier system has been excellent for any frequency between one and two megacycles. The audiosignal was taken from a tape recorder. The EOLM 301B has successfully modulated the laser beam with good fidelity.

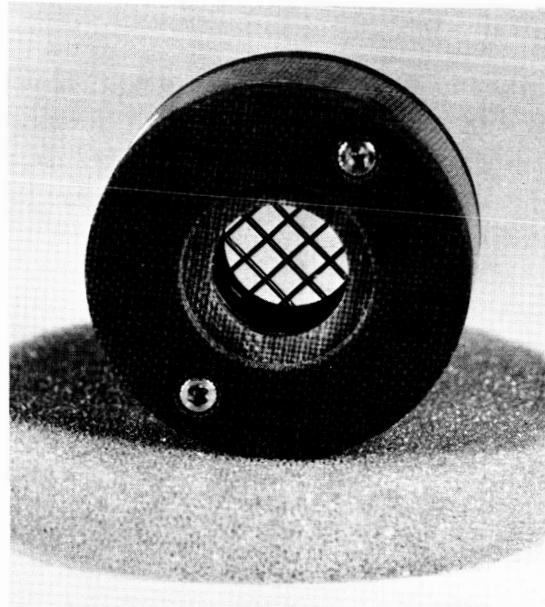


Figure 10—KD₂P crystal.

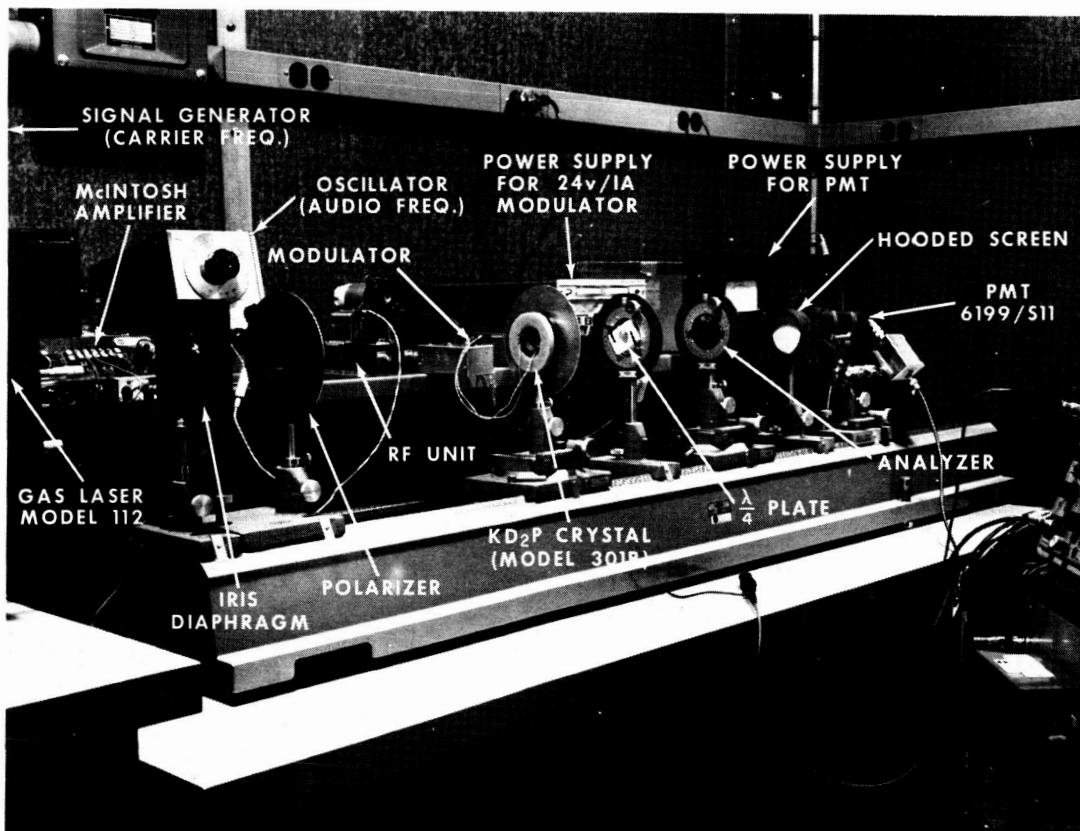


Figure 11—Electro optical light modulation experimental setup.

GaAs MODULATOR

Gallium arsenide (GaAs) is a promising electro-optic crystal material for light modulation in the infrared region. Figure 12 shows a GaAs modulator. The dimensions of the crystal are 3mm x 3mm x 1.7cm. Figures 13, 14, and 15 show the modulation and transmission vs. wavelength. A modulation depth up to 50 percent was obtained for a modulation voltage of 400 volts RMS. The electric field, E , is perpendicular to (1, 1, 1) plane, and

$$v_{\lambda/2} = \frac{1}{\sqrt{3}} \frac{\lambda}{r_{41} n_0^3} \frac{t}{\mathcal{E}}$$

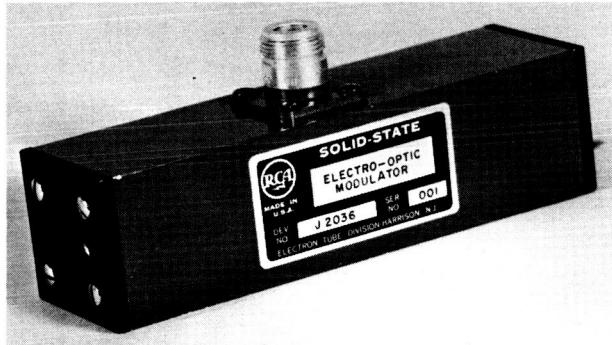


Figure 12—GaAs modulator.

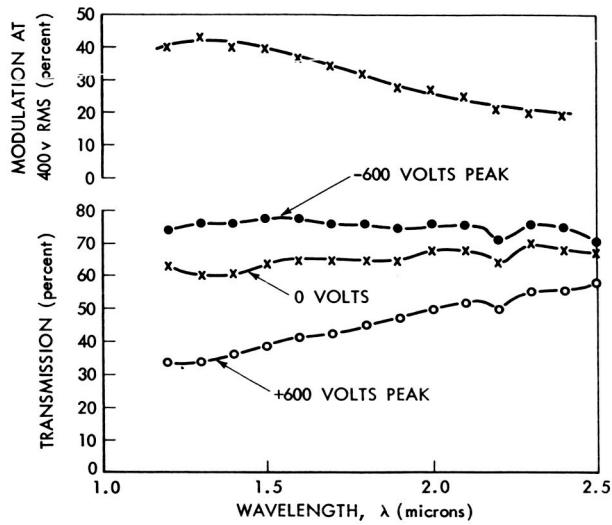


Figure 13—Percent modulation and transmission vs. wavelength for GaAs modulator ($\lambda/4$ plate = 8600 Å).

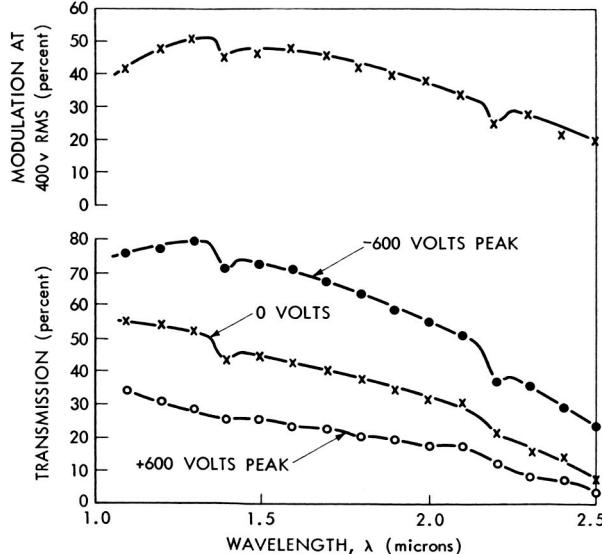


Figure 14—Percent modulation and transmission vs. wavelength for GaAs modulator ($\lambda/4$ plate = 1.03 μ).

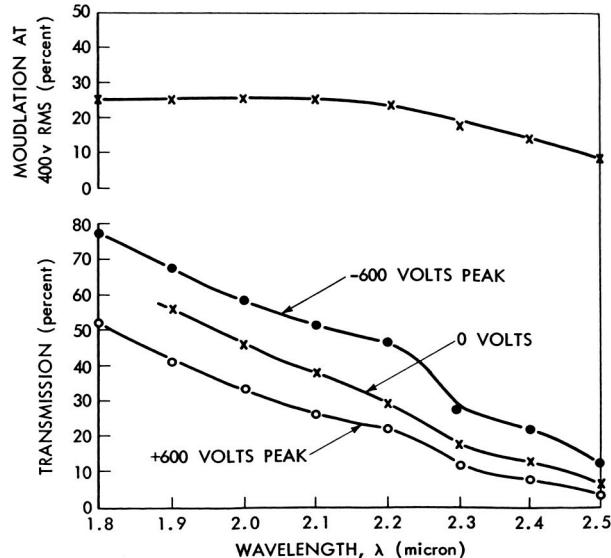


Figure 15—Percent modulation and transmission vs. wavelength for GaAs modulator ($\lambda/4$ plate = 2.0 μ).

A development program to increase the transmission of GaAs at wavelengths below 1.4 microns has been initiated. The intrinsic band gap absorption edge occurs at 0.86 microns in GaAs, and the absorption observed between 0.86 and 1.4 microns is due in part to impurities. An attempt will also be made to grow suitable GaP (gallium phosphide) crystals, which rough estimates indicate should require lower modulating voltages than GaAs. GaP is transparent to wavelengths as low as 0.6 microns and, therefore, could be used to modulate many visible and near infrared lasers.

The transmission loss of a GaAs crystal in the spectral band from 1.4μ to 16μ is negligible, practically all the attenuation being due to reflection at the ends of the crystal. Therefore, with antireflection coatings on its ends, the transmission of the crystal can be increased by approximately 48 percent. Because of this particular configuration, ($E \perp [1, 1, 1]$ plane), the crystal can be oriented in any direction of the light beam.

On the basis of these properties, it can be said that GaAs crystal is a practical device for modulating a laser beam at TV bandwidths. It is rugged, drive requirements are reasonable, and optical alignment is not critical. The half-wave voltage of GaAs is comparable to that of cuprous chloride (CuCl) at near infrared wavelengths. Also, in contrast to CuCl, long (5 cm and more) nonhygroscopic crystals of GaAs having high resistivity can be grown, cut, polished, and handled without introducing strains.

USE OF HMTA (HEXAMETHYLENETETRAMINE) FOR ELECTRO-OPTIC MODULATION

An investigation of the cubic piezo-electric crystals revealed that the most promising material in the visible region is HMTA (hexamethylenetetramine). RCA investigations of cuprous chloride for modulators were initially promising, but extreme difficulties in growing large and strainless single crystals have halted progress. HMTA, however, appeared to be readily growable in single crystals.

In March 1963, Dr. Richard McQuaid of Aircraft Armament, Inc., reported (Reference 3) that HMTA has electro-optic properties approximating those of KDP, but with wider optical apertures and with the electric field applied perpendicular, rather than parallel, to the direction of light propagation.

Dr. McQuaid achieved a one-half wave retardation with a relatively low applied voltage of 8.3 kv. From this he calculated a relatively high electro-optic coefficient of 7.3×10^{-10} cm/volt at $\lambda = 5475\text{\AA}$, or 6.0×10^{-10} cm/volt at $\lambda = 6328\text{\AA}$. The crystal dimensions were 2.89 mm in the direction of the applied voltage, and 3.25 mm in the direction of the light propagation. McQuaid investigated various sizes of HMTA crystals and reported various values of electro-optic coefficient. Other manufacturers (RCA, Texas Instrument, and GTE) have grown HMTA crystals and also reported various values of the electro-optic coefficient.

To investigate the use of HMTA for our own experimental laser program, three HMTA crystals were purchased from Aircraft Armament, Inc. Figure 16 shows an HMTA crystal, mounted between narrow electrodes to keep the capacitance small (approximately 2pf). The optical faces of

the crystal are protected from the atmosphere by flat glass cover plates, and the entire unit is sealed against moisture penetration. The optical faces and the electrodes are oriented to modulate in the transverse mode, with the electric field perpendicular to the light path. The length-to-width ratio is close to 10:1. The optical transmissivity is between 0.85 and 0.88.

The average electro-optic coefficients in the electrode region are given in Table 2.

The three HMTA crystals have been tested as modulators for a 6328 Å He-Ne laser beam with a pulsed CW subcarrier (100 Mc and 150 Mc) with repetition rate of 100 pps and pulse width of 1 ms, to avoid damage to the crystal.

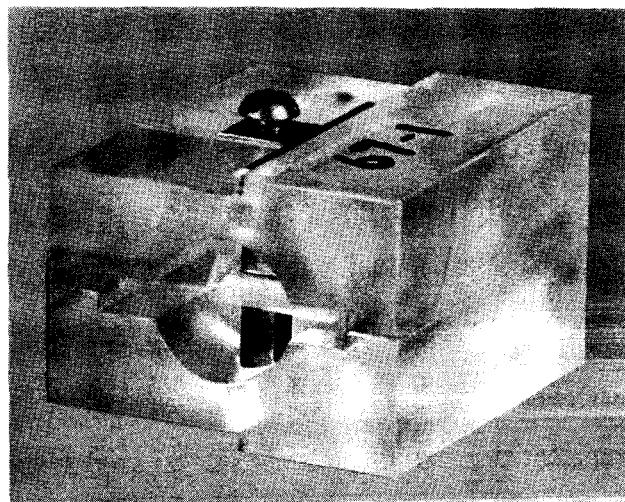


Figure 16—HMTA crystal.

Table 2

Average Electro-Optic Coefficients
in the Electrode Region.

Crystal Number	Electro-Optic Coefficient, r_{41} (cm/volts)	Half-Wave Retardation Voltage (calculated), $v_{\lambda/2}$ (kv)
64-2	0.465×10^{-10}	22.8
67-1	0.625×10^{-10}	13.1
67-2	0.566×10^{-10}	13.3

A comparison between the calculated $v_{\lambda/2}$ of the recently delivered HMTA crystals (nos. 67-1 and 67-2) and the earlier reported values shows that the half-wave retardation voltage $v_{\lambda/2}$ was about ten times higher than that reported earlier for small, perfect HMTA crystals. On the basis of this data, the use of HMTA as a light modulator does not appear promising at this time, the chief problem being the growth of large crystals which are free from imperfections, so that they will have values equivalent to those measured on the small perfect crystals.

(Manuscript received January 7, 1966)

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